NOISE GENERATION AND BOUNDARY LAYER EFFECTS IN VORTEX-AIRFOIL INTERACTION AND METHODS OF DIGITAL HOLOGRAM ANALYSIS FOR THESE FLOW FIELDS

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Abstract

Experimental investigations of aerodynamic sound generation due to vortex–airfoil interaction in transonic flow were performed. For that purpose two different experimental set–up have been applied: A vacuum operated transonic wind tunnel and a newly built shock tube. Flow visualization was accomplished by a Mach–Zehnder interferometer as well as by a holographic interferometer. The interferograms obtained were evaluated by an image processing system developed at the institute.

Two mechanisms of aerodynamic sound generation could be identified which are basically different from the dipole–like one which has been known from subsonic flow fields. The newly found sound waves are called "transonic waves" and "compressibility waves". For both of them simple models have been suggested which can explain their occurance and – at least partly – also their strengths.

Beside the sound generation, viscosity effects were investigated, such as flow separation at the leading edge, secondary vortices at the shoulder of the airfoil, and the Kutta–condition at the trailing edge. But in transonic flow their influences on the sound generation seems to be of secondary importance only.

Keywords: Aerodynamic noise; Great Britain; Vortex/airfoil interactions; Boundary layer; Transonic wind tunnels; Tomography

List of Keywords:

Noise
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Vortex noise
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High speed camera

EXPERIMENTAL INVESTIGATION ON BLADE–VORTEX INTERACTION

1. Experimental set–ups

For the experimental investigations two different set–ups have been used: A vacuum operated transonic wind tunnel and a shock tube.

1.1 Wind tunnel

In the transonic wind tunnel an undisturbed flow period of up to 20 seconds – depending on the Mach number and on the cross section – can be achieved. Windows of interferometric quality and with a diameter of 230 mm are mounted in the side walls of the tunnel for flow visualization.

Most experimental data were obtained by using a Mach–Zehnder interferometer in connection with either a high speed drum camera or a Cranz–Schardin camera.

The vortices are generated by a rectangular cylinder (von Kármán vortex street), they interact downstream with an airfoil. To confine, at least approximately, these interactions to single vortices a sufficiently large distance between two oncoming vortices is needed. For that purpose, the height of the tunnel section in which the vortices are generated has been enlarged. This allows for a vortex separation from the cylinder at a rather small local Mach number which implies small separation frequencies. Furthermore, a very well developed von Kármán vortex street with a very constant separation frequency is obtained for discrete Mach numbers by an acoustic feedback due to a standing sound wave normal to the mean flow direction, very much like a Parker mode. The details of the geometry of the transonic wind tunnel have been described in the 'Second Interim Periodic Report'.

In the experiments the Mach number of the flow, the distances of the vortices passing the airfoil, and the shape and size of the airfoil were varied.

1.2. Shock tube

In the newly built shock tube a single vortex is generated when a shock wave moves over a lifting airfoil. This vortex then interacts with a second airfoil. One advantage of this facility is the fact that the generated vortices have only very small core diameters and that they may approximately be regarded as potential vortices.

For the observation a real time holographic interferometer was constructed. The holograms themselves were taken by a thermoplastic film camera for instant recording and reconstruction. It is a characteristic property of the thermoplastic film material that good holograms can only be generated in a small range of spatial wave numbers. Furthermore, as this method allows for windows of ordinary quality, we could enlarge the diameter of the field of view to 400 mm. The details of the shock tube and the optical set–up have been explained in the 'Fifth Interim Periodic Report'.

In addition, pressure measurements were made simultaneously to yield correlations of the measured pressure signals with the interferograms.

2. Experimental results

In the transonic flow regime two new mechanisms of aerodynamic sound generation by vortex–airfoil interactions could be identified, they seem to be fundamentally different from the dipole–like sound known from subsonic flows.

2.1 Compressibility waves

When an incoming vortex passes the leading edge of the airfoil a sudden pressure increase in front of the airfoil is observed which itself is directly connected with the movement of the stagnation point due to an additional velocity distribution induced by the passing vortex. Later on, the stagnation point snappes back to its normal position while parts of the high pressure region cannot follow this motion. They separate, move upstream, and finally steepen up to a weak shock wave which is called a compressibility wave. Details and variations of this wave depend on the shape of the leading edge (round or sharp), spin and strength of the vortices (clockwise or contra–clockwise), and the mean velocity. However, compressibility waves do not seem to be affected by the details of the flow at the trailing edge. Details of these results have been reported in former interim periodic reports.

To study the far field of the compressibility waves additional experiments with a smaller airfoil (chord length 60 mm) were performed in the transonic tunnel recently. A typical series of interferograms taken by the Cranz–Schardin camera is shown in Fig. 1. In Fig. 2 density distributions are shown which were obtained by our image processing system. Picture 1 displays the corresponding steady mean flow, while pictures 2 to 4 present the unsteady shock waves at there different times. The flow very close to the vortex generator as well as the flow close to the airfoil could not be resolved. Therefore, at their locations space is left.

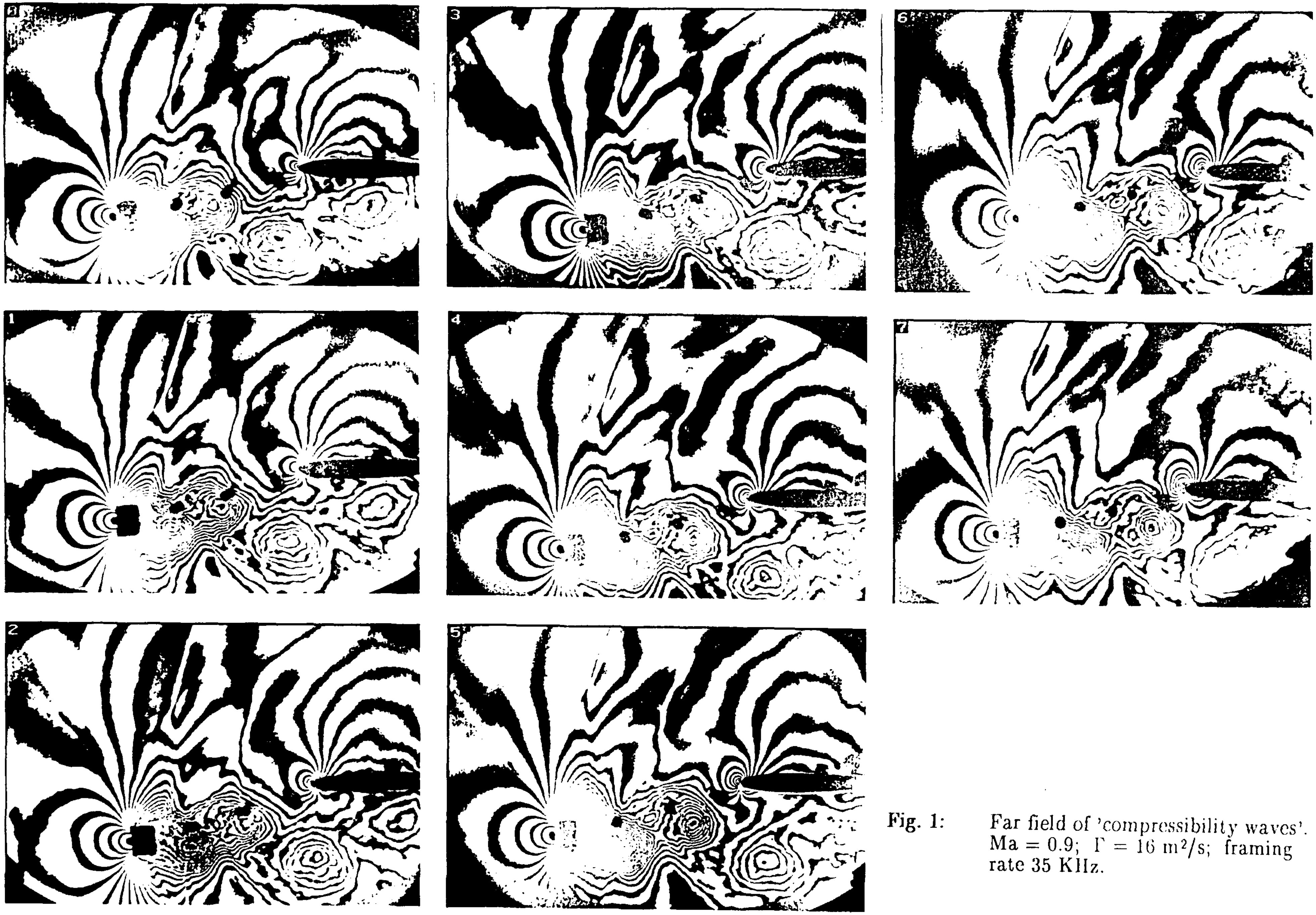

Fig. 1: Far field of 'compressibility waves'. Ma = 0.9; $\Gamma = 16\ m^2/s$; framing rate 35 KHz.

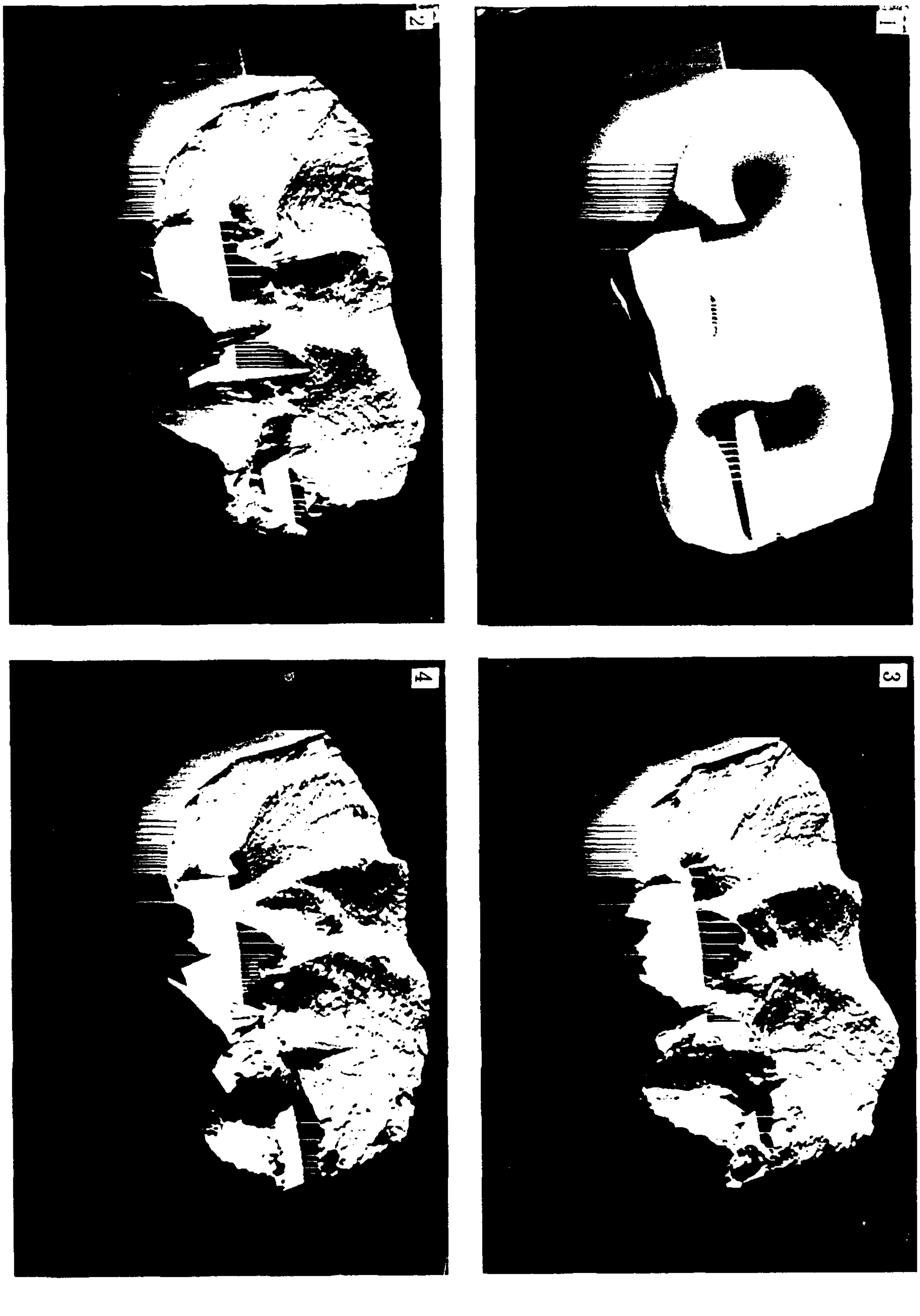

Fig. 2: Density distribution of the compressibility waves.
1: Mean flow; 2 to 4: correspond to 0, 4, 7 of Fig. 1.

In these experiments propagation of the waves can be pursued up to 15 d, where d is the thickness of the airfoil. Unfortunately, as these compressibility waves are disturbed by the vortex generator and by the incoming vortices their directivity pattern cannot be obtained completely.

In a second series of recent experiments in the transonic wind tunnel the interaction of counter–clockwise rotating vortices with three different airfoil shapes (NACA 0012, a blunt body, and a wedge) were studied. Here, all other parameters were kept constant. For the NACA 0012 profile and for the blunt body again compressibility waves have been found. In the experiments with the wedge–like shaped profile, a perhaps new wave has been discovered which preliminarly is named "separation wave" (see Fig. 3). Its likely relationship with the compressibility wave has not been investigated yet.

In the first picture of Fig. 3 one can see a separation bubble on the upper side of the wedge which grows in pictures 2 to 4. In the next stage (picture 5) it breaks down and is carried off by the flow. At the same time a "separation wave" is generated (pictures 6,7). On the last two pictures this wave travels upstream.

The generation of this new wave may be explained by a change of flow direction near the leading edge and by unsteady variation of stagnation region.

2.2.Transonic Waves

Depending upon the mean flow velocity and the velocity induced by an incoming vortex, an unsteady, locally confined supersonic flow region along one shoulder of the airfoil may occur. This supersonic region is terminated by a shock wave. After the vortex has passed the airfoil the shock wave will propagate with some time delay upstream. In some cases one gets not only a single shock but a cascade of them which then merge only at a later stage. This kind of sound generation has been called transonic waves. Details have been reported in former interim periodic reports.

For relatively large mean flow Mach numbers ($M = 0.8$) unsteady shock waves are also observed along the upper shoulder of the airfoil (Fig.4). When a clockwise rotating vortex passes the trailing edge the strength of the separating vortex sheet increases.

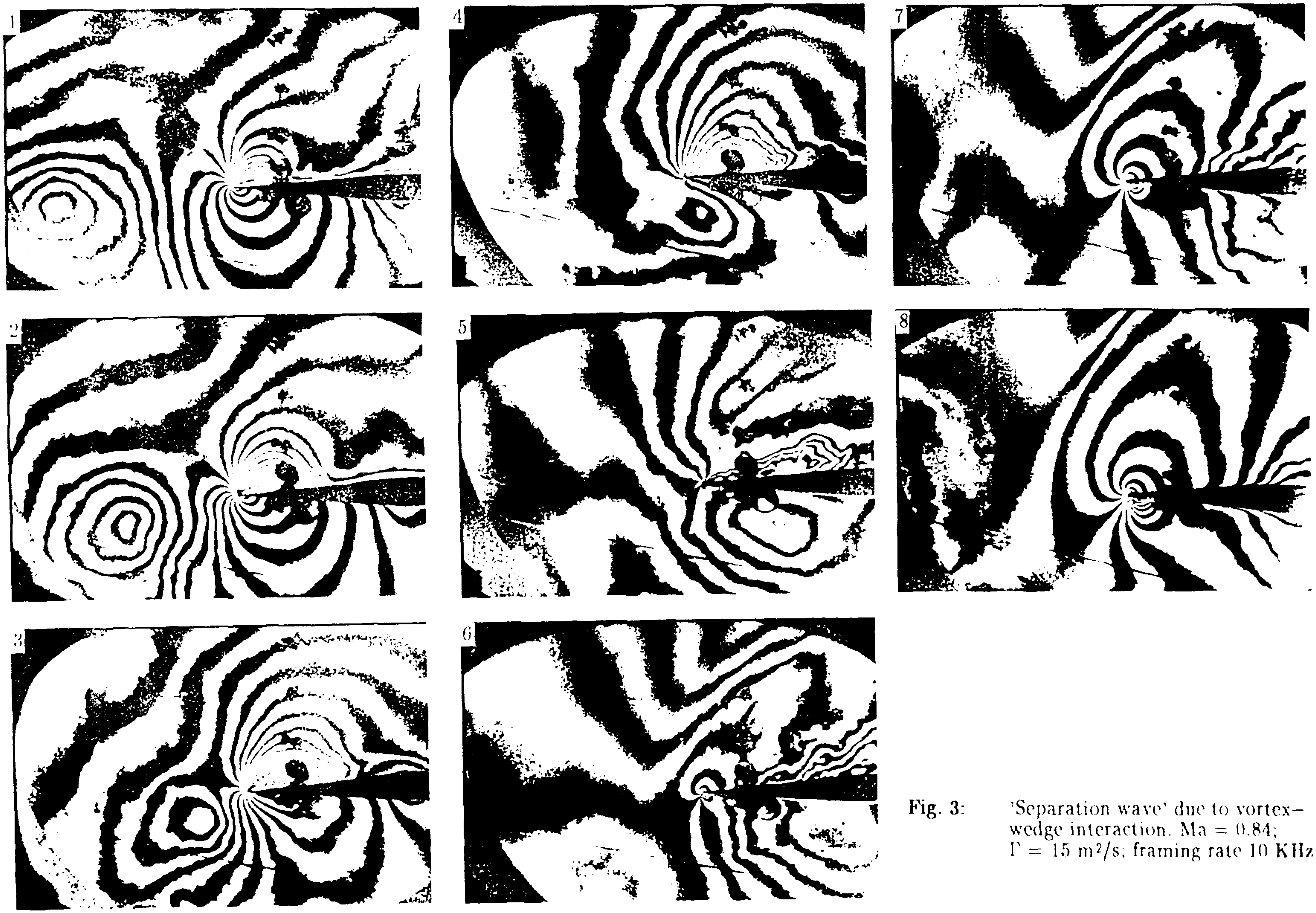

Fig. 3: 'Separation wave' due to vortex–wedge interaction. Ma = 0.84; $\Gamma = 15\ m^2/s$; framing rate 10 KHz.

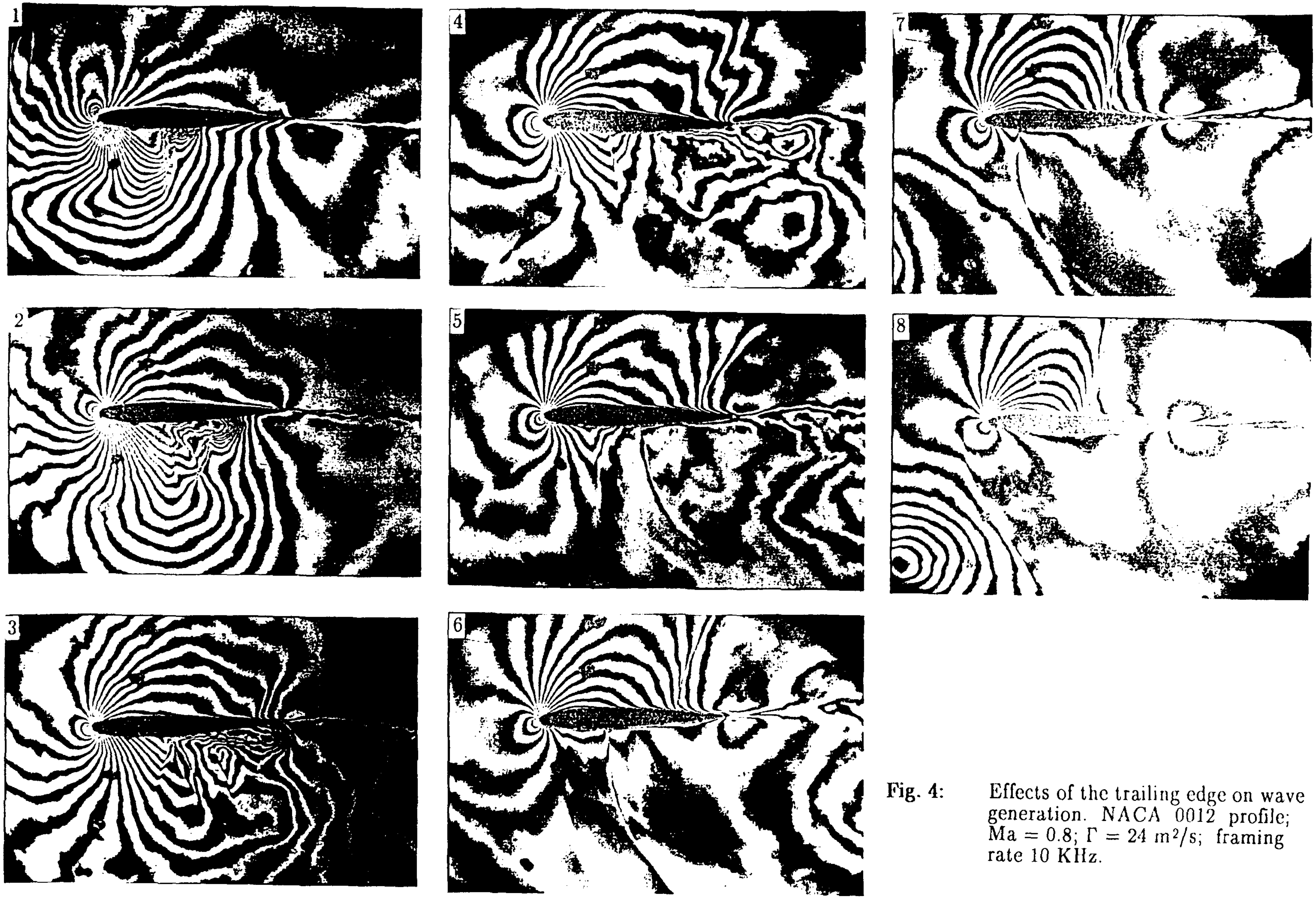

Fig. 4: Effects of the trailing edge on wave generation. NACA 0012 profile; Ma = 0.8; $\Gamma = 24\ m^2/s$; framing rate 10 KHz.

Simultaneously, the velocity along this upper side of the airfoil increases as well. In a second step the related possitive pressure gradient downstream of the high velocity area steepens and moves upstream. However, it is not quite clear yet in which cases this wave merge with the transonic wave generated at the lower side of the airfoil.

3. Models

In a transonic flow, where compressibility effects of vortex–airfoil–interactions become important, the actual source region can no longer be regarded as a compact one. This fact implies that the ordinary theories for compact flows cannot be applied. Furthermore, a generalized theory valid for non–compact flows which was developed independently by Ffowes Williams and Hawkings and by Möhring et al., respectively, is also of no real help here.

Therefore, simplified models for the compressibility waves as well as for the transonic waves are suggested.

3.1. Compressibility wave

The model describing approximately a compressibility wave is based on the assumption of the existence of a piston like source. For that purpose, it is required that the velocity induced at the surface of the leading edge of the airfoil has to be compensated by the velocity due to a piston source in order to fulfill the boundary condition $v_{normal} = 0$. A detailed desciption of this model has been given in the 'Sixth Interim Periodic Report'.

A comparison of the acoustic velocity estimated by our model and the acoustic velocity obtained from our pressure measurements agree at least in their general tendency, even though there still exist a systematic deviation of about 30 %. Nevertheless, if one accounts for all the inevitable errors the evaluation of the interferograms, the agreement between the model and the experimental data is still very satisfactory.

3.2 Transonic wave

Transonic waves can only occur if locally confined, unsteady supersonic flow regions are possible. From a simplified point of view, which accounts only partly for compressibility effects, one might expect that this happens if

$$v_{total} = v_{mean,profile} + \frac{\Gamma}{2\pi y_0} > c$$

is fulfilled (see Fifth Interim Periodic Report). Here v_{mean} is the mean velocity without vortices, Γ the circulation of the vortex, y_0 its distance to the airfoil normal to the flow direction, and c the speed of sound. This very simple estimation has been confirmed experimentally by variation of the parameters involved.

4. Tomographic Work

A software package has been developed for the evaluation of three–dimensional compressible flow fields recorded by means of Mach–Zehnder and holographic interferograms. Special attention has been paid to easy adaptability to experimental geometries and to computational efficiency.

Input data are given in the form of interferograms which are recorded with a CCD–camera and preprocessed in an image processor (VS–100, Imaging Technology). Using methods of digital image processing, interference fringes are extracted from the images. An object function is fitted to the fringes using an interpolation method developed in the institute. This object function represents the integral of the index of refraction taken along the line of view and serves as input data for the tomographic routines which compute the distribution of the index of refraction (density) of two–dimensional slices of the flow field.

The tomographic routines are based on a modified algebraic reconstruction technique using a special geometry making them sufficiently fast (approximately 1–2 min for reconstruction with a 100 x 100 mesh). They need considerably less time than the other steps of evaluation (recording, digital image processing and image correction).

The corresponding software is implemented on two VAXstations. For displaying the final results quasi–three–dimensional plots on a laser printer or colour–coded images on graphic terminals can be produced.

As a first nontrivial test weakly under– and overexpanded three–dimensional supersonic free jets from a Laval nozzle were investigated. Mach–Zehnder interferograms were taken from 16 angles and the density field in the jets reconstructed using the above mentioned methods. For more details we refer to the 'Fifth Interim Periodic Report'.

As a first step towards holographic tomography a holographic experiment has been set up recently. Holograms are recorded with an Argon ion laser and scanned by a CCD–camera mounted in such a way that it is movable around two different orthogonal axes.

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